Field Study of Energy Use-Related Effects of Ultraviolet Germicidal Irradiation of a Cooling Coil

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ABSTRACT

The energy use-related effects of ultraviolet germicidal irradiation (UVGI) to mitigate biological fouling (biofouling) of a chilled water cooling coil are investigated via a field study. A visibly bio-fouled cooling coil in an air-handling unit serving an operational building in a hot, humid climate is monitored for 5 months to establish a fouled coil baseline. Parameters monitored include air flow rate, airside pressure drop, air temperature and humidity upstream and downstream of the coil, chilled water flow rate, entering and leaving chilled water temperature, and waterside pressure drop. A UVGI coil irradiation system is installed on the downstream side of the coil following typical manufacturer guidelines, and the system is then passively monitored over a period of 14 months. The change in operation is estimated by comparing data from the baseline and post-irradiation periods. The 95% confidence intervals for average improvement of coil airside pressure drop and heat transfer coefficient are 11.07% to 11.13%, and 14.5% to 14.6%, respectively. Complexities of the physical phenomena involved, in particular, the combined effect of airflow and latent load on airside pressure drop, are taken into account.

INTRODUCTION

Finned tube cooling coils play a key role in the operation of air-conditioning systems. Coils are susceptible to fouling by particulate matter impinging on their closely spaced fins. Condensate that wets coil surfaces during operation helps to capture particles and also promotes microbial growth. Fouling increases airside pressure drop across a coil and decreases the air to water or refrigerant heat transfer coefficient. Both effects can increase energy use of an HVAC system significantly. This investigation considers the biofouling of chilled water coils and its mitigation by low power ultraviolet germicidal irradiation (UVGI) systems.

BACKGROUND

Airside Biofouling of Cooling Coils

Heat exchanger fouling is the buildup of organic and/or inorganic matter on the heat transfer surfaces. Cooling coils, due to the close spacing of fins on the air side (10 to 15 fins per inch or 4 to 6 per cm), can act as particulate

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filters and trap material such as dust, hair, debris, and microbes. Coil surfaces, by design, become wet during operation in many applications, thereby presenting growth opportunities for impacted microbes.

A number of studies quantify the benefits of cleaning a fouled coil. Most of these studies consider mechanical or chemical coil cleaning and do not distinguish between different types of fouling.

Montgomery and Baker (2006) describe a coil cleaning case study performed on two air-handling units (AHUs) serving part of a 34-story office building in New York City. Cleaning of coils resulted in a 14% decrease in pressure drop across the coils, an increase in ability to transfer sensible loads of 25%, and an increase of 10% for latent loads. Overall, coil cleaning appeared to have the potential to save 10%-15% in HVAC system energy consumption.

Yang, Braun, and Groll (2004; 2007a; 2007b) describe the energy use effects of coil fouling as measured in a laboratory study. The authors found that the energy penalty from the increased pressure drop across the cooling coil was more significant than that from the change in heat transfer coefficient. In some cases with lower amounts of fouling, the heat transfer coefficient was found to increase due to an increase in air velocity, but this was offset by the increased thermal resistance as fouling accumulates.

Biological particles that deposit and grow on a cooling coil contribute to increased energy use and IAQ problems (Siegel and Walker 2001; Siegel and Carey 2001). Single pass deposition in these studies ranged from 1% for 1.1 μm particles at low velocities of around 200 fpm (1.02 m/s), to 30% for 8 μm particles at high velocities of 1024 fpm (5.2 m/s).

Ali and Ismail (2008) collected fouling material from room air conditioners, classified its biological and non-biological components, deposited it in increasing amounts on a DX cooling coil in a laboratory apparatus, and measured the resulting degradation in performance. The organic component of the fouling material comprised 18.4% of the mass on the upstream face of the coil and 1.2% on the downstream face. The organic component consisted of masses of Aspergillus fungal colonies. The coefficient of performance (COP) of the unit dropped from a clean value of 2.82 to fouled values of 1.89, 1.73, and 1.23 after the injection of 100g, 200g, and 300g (0.22 lbm, 0.44 lbm, and 0.66 lbm) of fouling material, respectively.

Pu et al. (2010) seeded a cooling coil with biological material and recorded the airside pressure drop and heat transfer coefficient resulting from different levels of fouling after 28 days of growth. They found a range of -15.6% to 13.1% for the heat transfer coefficient and 19.8% to 43.1% for the air-side pressure drop fouling factors.

UVGI for Control of Biofouling

The UVC (or UV-C) wavelength band of ultraviolet light inactivates biological organisms by disrupting their DNA and rendering them unable to reproduce. UVC generated by low pressure mercury vapor lamps is used both for air and surface disinfection in HVAC systems. The basics of UVGI coil treatment systems are described by ASHRAE (2008) and Kowalski (2009), which both review numerous sources on the subject. The devices are installed upstream, downstream, or on both sides of the coil. Bahnfleth (2011) provides a recent review of the technology used in air handlers and summarizes published reports of its effectiveness. At the time of its publication, there were no peer-reviewed studies of the energy use impacts of UVGI for coil treatment applications.

Several published reports describe the ability of coil surface UVGI to mitigate or prevent coil fouling but without quantitatively assessing the impact on system energy use. For example, Shaughnessy, Rogers, and Levetin (1998) documented the effectiveness of UVC in reducing contaminant concentrations on various AHU surfaces, and did extensive microbe classification, but did not measure energy impacts. Levetin et al. (2001) also demonstrated the effectiveness of UVGI in reducing surface contamination without reporting energy use-related data.

In a brief trade magazine article (Steril-Aire 2000a, 200b), a manufacturer describes the installation of UVC surface treatment technology in a facility's twenty AHUs to address IAQ-related problems, and the resultant energy benefit. The article claims that the facility experienced a 28% reduction in HVAC energy use. Unfortunately, the reporting of energy savings is missing many details.

Keikavousi (2004) describes the results of a number of coil cleaning UVGI installations throughout a Florida hospital system. An AHU with a visible buildup of mold (estimated 50% of coil face area) was selected for initial testing. Following installation of UVGI, static pressure drop across the coil decreased from 1.8 to 0.7 in wg (448 to 174 Pa), face air velocity increased from 230 to 520 fpm (1.17 to 2.64 m/s), and leaving wet bulb temperature decreased from 57 to 53°F (13.9 to 11.7°C).

A California Energy Commission study (Arent 2006) found a 1-2% airflow improvement due to the installation of coil surface UVGI, which was noted as positive but not statistically significant. No efficiency improvements were found. The study was performed on 54 schools: an 18 school control group and two study groups. They note, importantly, that fouled coils were not targeted for this study and little coil fouling was observed pre-intervention, so the results were perhaps predictable.

Blatt, Okura, and Meister (2006) report on a number of UVGI installations in schools (including the aforementioned California Energy Commission study) and other commercial buildings that showed energy savings through improvement in coil operation.

Recent conference papers on research in progress by Luongo and Miller (2014) and Yi et al (2014) present promising preliminary results of coil fouling studies.

OBJECTIVE

The objective of the research is to quantify the energy benefit of using UVGI for mitigation and prevention and biofouling on a chilled water coil. This is accomplished by monitoring the performance of a visibly fouled cooling coil in an operational AHU, installing generic UVGI equipment per manufacturer design recommendations, and then monitoring performance after turning the lamps on. The two measures examined are change in airside pressure drop, and change in heat transfer coefficient.

METHODOLOGY

Conceptually, the research plan is a simple before/after experiment, but with a number of complexities involved.

Experimental Site

The experimental site is an AHU in an occupied laboratory classroom building on a college campus in Tampa, FL. The variable air volume (VAV) AHU has a design supply air flow rate of approximately 6000 cfm (2.832 m^3/s), which was estimated based on coil face area and typical design velocity due to lack of design documentation. The chilled water coil is 60 in. wide by 33 in. high (152.4 cm by 83.8 cm) and 6 rows deep. Outdoor air flow rate varies from 500 to 1500 cfm (0.236 to 0.708 m^3/s) due to an interlock with fume hoods in the classrooms. The site was chosen based on a combination of factors: visibly fouled cooling coil, owner interest, researcher access, and climate. Climate aids in acquiring a broad range of airflow, sensible load, and latent load. The relatively long cooling season also aids with accruing sufficient data.

Two rows of UV lamps were installed 12 in. (30.5 cm) downstream of the cooling coil. The lamp power and arrangement design resulted in an average surface irradiance of 327 $\mu W/cm^2$ and minimum of 180 $\mu W/cm^2$ (0.304 W/ft^2 and 0.167 W/ft^2, respectively). To verify the design, irradiance measurements were taken 3 inches (0.0762 m) from the coil face after 6 months of operation and roughly extrapolated to values at the coil surface using the analytical solution for an infinite line source. The extrapolated measurements predicted an average irradiance of approximately 300 $\mu W/cm^2$ and a minimum of about 200 $\mu W/cm^2$ (0.279W/ft^2 and 0.186 W/ft^2).

Measurement

The data acquisition setup measures all points necessary to characterize cooling coil operation, as well as other items of interest, at 1 minute intervals (Table 1). Data collection is passive, i.e., the data collected is all from the building's normal operation over a period of many months, not from a controlled set of experiments.

Table 1. Measurement Points

	Measurement	Accuracy
Airside	Supply Air Flow Rate	±2% of reading
	Airside Pressure Drop	±0.14% of reading
	Entering and Leaving Air Temp	±0.11°F (±0.2°C)
	Entering & Leaving RH	1% RH
Waterside	Chilled Water Flow Rate	1% of reading
	Entering and Leaving Water Temp	±0.11°F (±0.2°C)
	Waterside Pressure Drop	±0.14% of reading
Power	Fan Power	±0.1% of reading
	UV Ballast Power	±0.1% of reading

Most of the measurement points pertain to the two previously mentioned measures of interest: airside pressure drop and heat transfer coefficient. The pressure drop is primarily influenced by airflow, but also by the amount of water on the coil (ASHRAE 2012). One way to quantify this is latent load, which is calculated from the airflow and the upstream and downstream air conditions. The heat transfer coefficient necessitates the use of air and water flow rates, as well as the upstream and downstream conditions. Fan power is measured in an attempt to relate it to airflow, though the effect of other parts of the air system makes this not as useful as one might hope. UV power is measured for future energy analysis.

Data Analysis

Pressure Drop. Accurate comparison of the coil pressure drop before and after application of UVGI requires controlling for airflow and latent load. One cannot simply perform a t-test between the "before" and "after" data pressure drop data. The comparison method adopted employs regression analysis to quantify the effect of the UVGI intervention. The form of the equation chosen is based on the Darcy-Colebrook equation:

$$\Delta P = \left(\frac{f\,L}{D_h} + \sum C \right) \frac{1}{2} \rho v^2 \tag{1}$$

A key consideration is the primary influence of velocity pressure. For a dry coil, the constants inside the parentheses of Eqn. 1 are dependent on the construction geometry, e.g., fin spacing, tube size and placement. However, for a wet coil the amount of water on the coil alters the dry values of several key parameters. The construction of a regression equation involves art, trial, and error, as well as theoretical considerations, which will not be reviewed in their totality. The regression form adopted in this case is:

$$\Delta P = \beta_1 Q^2 + \beta_2 Q^2 q_l + \beta_3 Q^2 t + \beta_4 Q^2 q_l t + \beta_5 Q^2 s + \beta_6 Q^2 q_l s + \beta_7 Q^2 ts + \beta_8 Q^2 q_l ts \tag{2}$$

Eqn. 2 reflects the primary influence of velocity pressure (using airflow as a surrogate), while also including the effects of latent load and time. The form of Eqn. 2 is such that pressure drop is zero when airflow is zero, as must be the case. The term s is a categorical variable, coded 0 for all data points before the lamps are turned on and coded 1 for all points after. This means that the entire second half of the equation is 0 before the lamps are turned on. When $s=1$, the second half of the equation represents the difference between the lamps off and lamps on states. For example, $\beta_1 Q^2$ is the influence of velocity squared alone on the baseline data, $\beta_5 Q^2$ is the change in influence resulting from the lamps being turned on, and $(\beta_1+\beta_5)Q^2$ is the influence of airflow squared on the lamps-on data.

Changes to the data and regression equation are made using formal methods: regression outliers are identified and deleted using one pass of a Bonferroni outlier test (α=0.05), and adjustment of the coefficients uses weighted least squares to reduce predictor influence on variance of residuals.

The before/after pressure drop are compared in two ways. The first is by using Eqn. 2 to construct the family of pressure drop vs. flow curves with latent load as a parameter. The second is to use Eqn. 2 to predict the pressure drop values corresponding to a year of measured airflow and latent load data. In each case, the pressure drop before UV ($s=0$) and after UV ($s=1$) is compared.

Heat Transfer. Heat transfer effectiveness is the fractional relationship of actual heat transfer to theoretical possible heat transfer:

$$\varepsilon = \frac{q_{actual}}{q_{\max}} = \frac{\dot{m}_{air}\left(h_{in} - h_{out}\right)}{\min\left\{\dot{m}_{air}\left(h_{in} - h_{w,sat}\right), \dot{m}_w Cp_w\left(T_{a,in} - T_{w,in}\right)\right\}} \quad (3)$$

Values are calculated for all baseline data, and all post-UV data. The two sets of effectiveness are then compared with a t-test at α=0.05. Rather than use the standard deviation calculated from the sample itself for the t-test, a more conservative average standard deviation was calculated through uncertainty propagation (ASHRAE 2004).

This method is compared with an enthalpy based heat transfer coefficient normalized to a single operating point. The procedure involved is an inverse application of a procedure used in energy simulation software for calculating an off-design heat transfer coefficient (UA) given a design value (US Department of Energy 2014). This method allows a UA at uniform reference conditions to be computed at all time steps. For the sake of brevity, the specifics will not be reviewed here. Similar to effectiveness, the average standard deviation is calculated via uncertainty propagation.

RESULTS

The baseline, or still fouled, data were collected at one minute intervals from mid-June through mid-July, and from mid-September through the end of November, 2013, totaling around 87,000 data points. The lamps-on, or post-intervention, data were collected at one minute intervals between November 2013 and December 2014, totaling approximately 530,000 observations.

Airflow and Pressure Drop

As noted previously, coil airside pressure drop is a function of airflow and latent load. A least-squares regression is performed, followed by a formal elimination of outliers using Studentized residuals, and a weighted least squares regression to eliminate unequal variance in residuals. The original coefficients yielded $R^2=0.9796$. The outlier elimination removed approximately 1800 data points out of the 600,000. This mainly served to cull isolated values at far upper and lower ends of the pressure drop range that seemed incompatible with their reported airflow. The weighted least squares equation has $R^2=0.9963$. All coefficients in both equations have a $p\text{-}value < 2e\text{-}16$.

The final regression equation is evaluated for airflows of 3500-5250 cfm (1652-2478 L/s) and latent load of 0-102.4 kBTU/h (0-30 kW) on a 50 x 50 grid. The mean difference is 0.135 in. wg (0.336 kPa) with a 95% CI 0.130 to 0.140 in. wg (0.0324-0.0349 kPa), or reduction of 12.0%. Evaluation for a year of airflow and latent load data yields a mean difference of 0.095 in. wg (0.0237 kPa) with a 95% CI 0.0946 to 0.0952 in. wg (0.0236 to 0.0237 kPa), or reduction of 11.1%. The differences in before and after performance for the same sets of data can be seen in Figure 1. This demonstrates that 1) there is a statistically significant difference due to the application of UVGI 2) actual operating patterns need to be taken into account when evaluating benefits. An average over a grid of values can give a general idea, but not picking a correct range (i.e. limited by the data used to create the regression) can be hazardous extrapolation.

Effectiveness and Heat Transfer Coefficient

Effectiveness of heat transfer is an attractive and simple to understand metric, but changes based with entering air and water conditions. Comparisons of effectiveness are only valid if performed for similar conditions. This is also true of heat transfer coefficient (*UA*). However, as noted previously, a UA value normalized to reference conditions can be computed to permit a fair comparison. Figure 2 illustrates the difference between the two methods. The left-hand figure appears to show that the post-UV data has lower effectiveness with a 95% CI of 1.52 to 1.65 percentage points lower. However, the input conditions of the baseline and lamps-on states do not occur with equal frequency, suggesting that the lack of a "one for one" comparison is skewing the results. The right-hand figure indicates a consistent increase in average heat transfer coefficient with a 95% CI of 14.5% to 14.6%. The UA is enthalpy based via converting a Btu/h-F (kW/C) value to Btu/lbm-F (kJ/kg) via dividing by specific heat, hence the mass/time units.

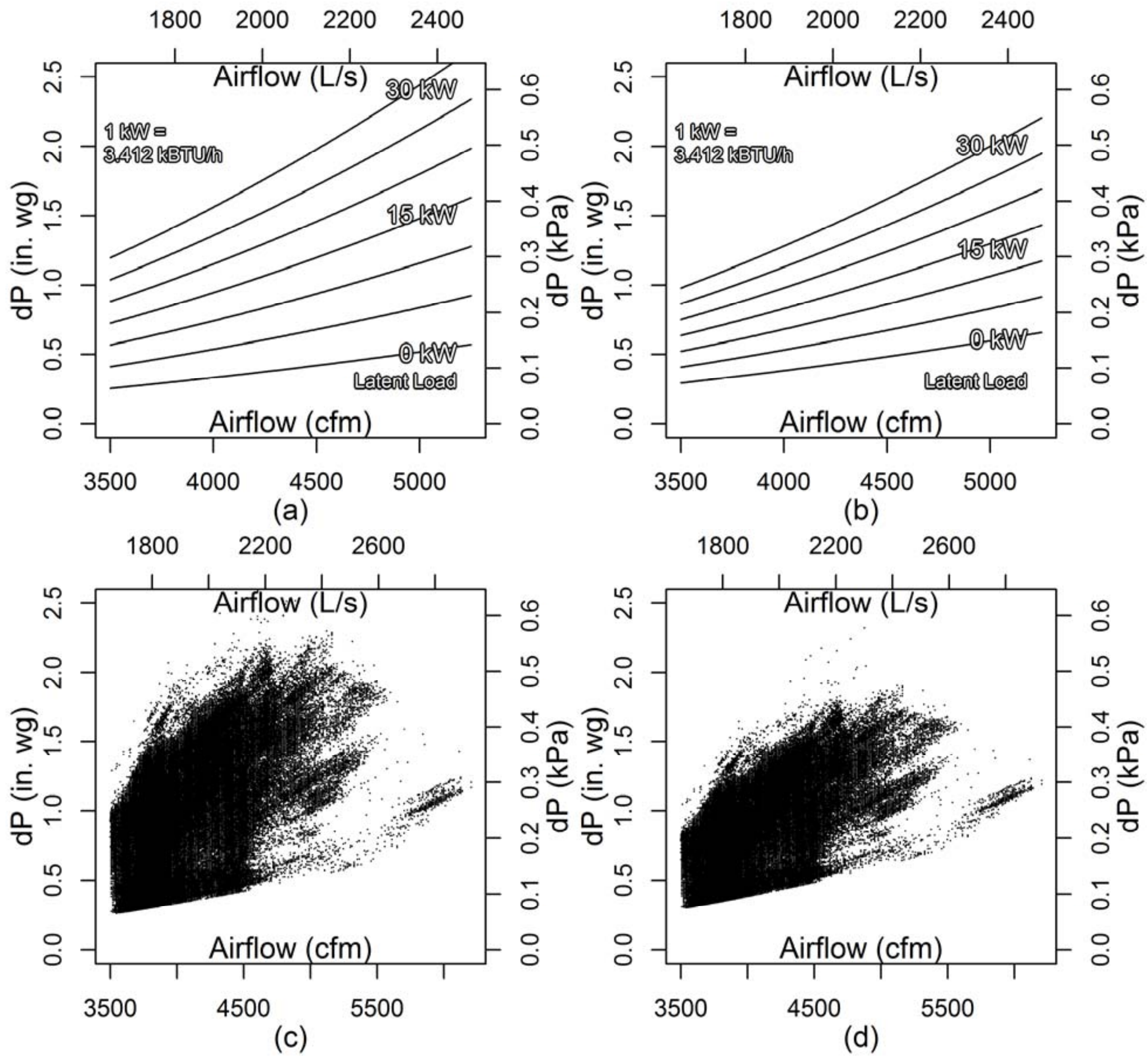

Figure 1 dP vs. airflow as a function of latent load – (a) baseline and (b) post-UV.
Predicted dP for a year of airflow and latent load data – (c) baseline and (d) post-UV.

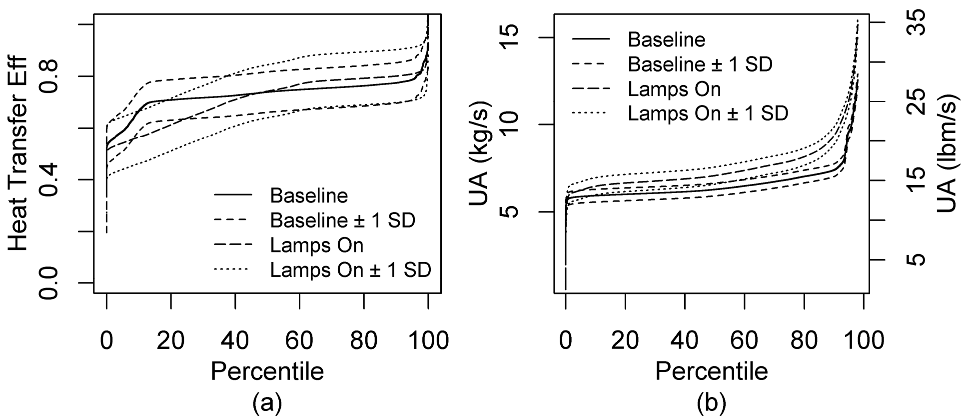

Figure 2 Cooling Coil Performance (a) effectiveness, value and ±1 average standard deviation (b) Heat transfer coefficient at reference point, value and ±1 average standard deviation, 98% of values shown for clarity

DISCUSSION

Pre-processing of the data was necessary for analysis. This involved eliminating physically unrealistic data points that could indicate maintenance or AHU panels being opened, such as negative pressure drop across the coil. Also removed were data where the value of interest was close to zero, indicating a shut off or similar condition, such as airflow less than 100 cfm (0.0472 m^3/s), or calculating latent load when the waterside temperature difference was within measurement error. A field site was chosen instead of laboratory so as to have realistic fouling conditions. The trade-off was the significant data noise and remote access issues that come with field studies, and the inability to employ a typical experimental design for the data collection. The results are for a single building, in a single climate, over a specific time period and conditions. More data is necessary to draw general conclusions.

CONCLUSIONS

The application of UVGI on fouled cooling coils in an operating AHU shows a 10% decrease in pressure drop and a 14.55% increase in heat transfer coefficient at reference conditions. The methods demonstrate ways to analyze pressure drop and heat transfer coefficient data in the absence of a traditional experimental design. Future work includes another field site, energy modeling using the results of experimental data, and epidemiological modeling.

ACKNOWLEDGMENTS

The authors acknowledge with gratitude financial support for completion of this work by ASHRAE under RP-1738, initial funding by the Consortium for Building Energy Innovation (CBEI), donation of UV equipment and design services by UVDI, Inc., and to the owner for access to the site.

NOMENCLATURE

C = loss coefficient

Cp_w = specific heat of water

ΔP = pressure drop

D_h = hydraulic diameter

ε = heat transfer effectiveness

f = friction factor

h_{in} = enthalpy of air entering coil

h_{out} = enthalpy of air leaving coil

$h_{w,sat}$ = enthalpy of air if cooled to saturation at temperature of entering water

L = length of conduit

m_{air} = mass flow rate, air

m_{water} = mass flow rate, water

Q = volumetric airflow rate

q_{actual} = actual coil heat transfer

q_l = latent load

q_{max} = maximum coil heat transfer

ϱ = density

s = categorical variable, state denoting pre (0) or post (1) UVGI treatment

$T_{a,in}$ = temperature of air entering coil

$T_{w,in}$ = temperature of water entering coil

t = time

v = velocity

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